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Refining Boat Electrofishing Equipment to Improve Consistency and Reduce Harm to Fish

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Abstract.—A major concern with electrofishing is the standardization of sampling equipment and methods, particularly when collections are used to monitor spatial and temporal changes in fish communities. Standardization can not only ensure that stock assessment is consistent—that is, the data collected over time and space have equal meaning and are not influenced by differences in gear or gear application—but also reduce injury by constraining power to ranges that are likely to immobilize fish but unlikely to harm them. Standardization of electrofishing equipment requires adjusting power output to keep constant the amount of power transferred to fish in diverse water conditions. In this study, the power level thresholds required to immobilize and injure fish under controlled laboratory conditions were identified for various size–species combinations and applied to establish power minima and maxima suitable for successful and safe boat electrofishing. The target settings identified allowed survival of 99.4% of the fish collected and held for 2–3 h during field trials; all the mortalities were small fish (≤53 mm long). The standardization procedure described herein may be adapted to single boats or fleets and can promote consistency in electrofishing, although it does not completely avoid harm to fish. Because electrofishing is an active capture method applied to changing microenvironments, complete standardization and total avoidance of harm to individual fish are not feasible with present technology, but standardization of controllable variables is advisable.

Electrofishing is commonly used for monitoring the status of fish populations in inland waters. The appeal of electrofishing as a collection tool is derived from its ability to produce adequate samples of selected fish species over a broad range of aquatic habitats and environmental conditions, with minimal personnel requirements, without exceedingly demanding physical activity, and with easily transportable, durable equipment that requires rather modest upkeep and handling. A further advantage is that although multiple fish species and sizes are susceptible to electrofishing, only target specimens may be retrieved and handled, and all or most of the specimens handled may be released uninjured.

A major concern with electrofishing is the standardization of sampling equipment and methodology (Heidinger et al. 1983). Standardization is the design of a set of equipment and procedures that is applied consistently. The purpose of standardization is to ensure that stock assessment is consistent: Data collected over time and space have equal meaning and are not influenced by differences in gear or gear application. Standardized procedures are particularly important when data are used to monitor changes in fish assemblages. Standardization of equipment and methods can increase consistency of survey data (Bonar and Hubert 2002); without standardization, differences among collections can be attributed to unknown levels of disparities in collection efficiency, rather than solely to dissimilarities in fish assemblages.

Standardization of power to safe levels can also reduce injury to fish. Exposure to electric current can lead to harm, particularly tissue hemorrhage and spinal injury, and can even cause immediate or delayed mortality (Snyder 1995). Dolan and Miranda (2004) reported a high rate of mortality in small, warmwater species exposed to elevated peak power densities; they suggested that limiting power output to what is necessary for immobilizing only large fish would reduce or eliminate high levels of mortality. Standardization can help constrain power to ranges likely to produce immobilization but unlikely to produce injury or mortality.

The difficulties associated with standardizing electrofishing are linked to equipment flexibility and strong dependency of gear efficiency on environmental distinctiveness. Flexibility is granted by the adjustability of a system of electrode arrays and by the diversity of electrical settings relative to output power and the frequency, width, and

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shape of the power pulse. Electrofishing is an active capture method applied to changing physicochemical conditions produced by seasonal climatic patterns (e.g., temperature, precipitation), as well as by differences in microhabitats (e.g., depth, substrate). Therefore, a mixture of environmental variables influences electrofishing effectiveness, although water conductivity is indeed the most influential (Reynolds 1996).

Standardization of electrofishing requires adjusting power output to keep the amount of power transferred to fish constant over diverse water conditions (Reynolds 1996). The power must be high enough to elicit momentary immobilization and low enough to avoid injury, or at least to reduce risk to tolerable levels (Schill and Beland 1995). Here is reported the power levels required to immobilize and injure fish, as assessed under controlled laboratory conditions; the use of these thresholds to establish power minima and maxima suitable for successful and safe field electrofishing, considering variability in water conductivity; and, once target settings have been identified, the validation of this application under field conditions.

Methods

Laboratory assessments.—Threshold power levels for immobilizing and injuring fish were determined indoors in a polyethylene tank measuring 1.8 × 0.8 × 0.8 m (length × width × depth). The tank was filled to a depth of 10 cm with well water. The cross- sectional profile of the tank was fit with two 1.6-cm-thick aluminum plate electrodes distanced (d) 65 cm apart, perpendicular to the longitudinal axis of the tank. These thick electrodes were necessary to avoid warping that would distort the electrical field. Electricity was supplied to the plates by way of a Smith-Root 15-D POW unit (Smith-Root, Inc., Vancouver, Washington) modified to allow continuous rather than discrete voltage control and equipped with additional smoothing capacitors to eliminate spikes and reduce ripples at the peak of pulses. Conditions within the tank produced a homogeneous electrical field with a constant voltage gradient, verified through in-water measurements. Because electrofishing effects depend on ambient conductivity rather than the specific conductivity provided by many meters (Reynolds 1996), ambient water conductivity (C_w; µS/cm) and temperature (T_w; °C) were recorded with a YSI 30 m (Yellow Springs Instruments, Yellow Springs, Ohio).

Fish were exposed to 60-Hz pulsed DC electrofishing. This setting was selected because it is commonly available in commercial electrofishers and because an informal survey of agencies that monitor warmwater fish with electrofishing identified the 60 Hz setting as being frequently used. Pulse widths were fixed at 1 and 6 ms because they represented settings near the upper and lower range of adjustments available in commercially available units. Nevertheless, in some units, pulse width is adjusted automatically and cannot be manipulated independently. For instance, in the Smith-Root GPP electrofishers, pulse width changes between 1 and 5 ms, depending on voltage (Smith-Root, Inc. 1999; Miranda and Spencer, in press). Peak voltage (V) was measured within the energized field with a Tektronix THS720A oscilloscope (Tektronix, Inc., Beaverton, Oregon). Following Kolz and Reynolds (1989), power density applied to the water (D_a; µW/cm^3) can be described as follows:

$$D_a = C_w \cdot \left(\frac{V}{d}\right)^2. \tag{1}$$

The electrical treatments were applied to four species at various sizes, representing a total of 11 separate species–size treatments (Table 1). These species–size combinations were selected because they were available from local fish-culture facilities. However, limited fish availability did not allow application of all treatments to all species–size combinations. Before they were tested, fish were seined from culture ponds, held in concrete raceways for at least 2 weeks, and maintained in good health on a diet of prepared food. During testing, randomly selected fish were transferred one at a time to the test tank and confined in the area between the two electrodes. After allowing 3–10 s for the fish to orient, and observing when the fish was positioned perpendicular to the electrodes, the current was switched on for 15 s. A fixed perpendicular position was chosen because of reports suggesting that the effect of the electric field may vary depending on the orientation of the fish (Lamarque 1990). The set of fish within a treatment was exposed to peak voltages incremented from near zero to levels exceeding those needed to immobilize them within 3 s, but each fish was treated only once. After an immobilization threshold had been approximated, additional observations were made at smaller voltage increments to more precisely pinpoint the threshold. The 3-s period estimated the time within which if the fish was not immobilized, it would likely escape the electrical field; the 15-s period estimated

TABLE 1.—Lengths, weights, and sample sizes (*N*) of species included in laboratory trials designed to identify immobilization and injury thresholds on fish exposed to 60 Hz of pulsed DC, with 1- and 6-ms pulses.

Species	Pulse width (ms)	Total length range (mm)	Total weight range (g)	*N*
Channel catfish *Ictalurus punctatus*	1	55–82	1–3	33
	6	53–82	1–3	35
	1	145–187	23–51	25
	6	147–186	24–49	25
	1	279–343	169–335	27
Largemouth bass *Micropterus salmoides*	1	47–71	1–5	28
	6	44–71	1–5	30
	1	219–328	138–385	26
Bluegill *Lepomis macrochirus*	1	61–81	4–10	30
	6	63–80	4–9	30
Black crappie *Pomoxis nigromaculatus*	1	137–181	33–73	25

the maximum amount of time that a fish might be exposed to electricity in an actual field setting. The number of fish tested per treatment ranged from 25 to 35, including 2–4 controls (i.e., the field was not energized when they were between the two electrodes). The reactions of each fish were observed and recorded, and video-taping with a camera positioned over the tank allowed review of immobilization responses to verify the accuracy of live observations.

After treatment, fish were transferred to separate, aerated 38-L holding tanks, and held for 18 h to allow potential hemorrhages to develop and to determine short-term mortality. Fish that remained alive after the holding period were killed in a solution of 100 mg/L MS-222. All specimens were kept on ice until viewed by radiography within 2 h. Radiographs were examined for evidence of spinal injury (i.e., compression, misalignment, or fracture of the vertebral column). A certified radiologist reexamined radiographs to verify interpretation of spinal injury, and to help differentiate among congenital abnormalities, past injuries, and injuries attributed to the electroshock exposure. Immediately after radiography, all fish were necropsied to evaluate tissue hemorrhage. Necropsy included filleting the length of the body just posterior to the pectoral fins, along the rays and spine, to the caudal peduncle.

Field strength descriptors such as voltage gradient (V/cm), current density (A/cm^2), or D_a (μW/cm^3) have traditionally been used to characterize electrofishing effects. Kolz (1989) suggested that immobilization thresholds depend in part on the fraction of D_a that is actually transferred from the water to the fish. A model presented by Kolz (1989) adjusts the power applied to the water by compensating for the inefficiency of transfer to the fish. The model relies on differences in the effective conductivity of fish and the conductivity of water to estimate the power that must be applied to waters of various conductivities to deliver a constant electric power to fish. Miranda and Dolan (2003) tested Kolz's model and reported that it closely predicted D_a thresholds required to immobilize fish over water conductivities ranging from 12 to 1,030 μS/cm, for various DC and pulsed-DC settings. According to Kolz's model, the power transferred into the fish (D_m, μW/cm^3) is a function of D_a, C_w, and the effective conductivity of the fish (C_f, μS/cm) and is estimated as follows:

$$D_m = D_a \frac{\left(4\frac{C_f}{C_w}\right)}{\left(1 + \frac{C_f}{C_w}\right)^2}. \qquad (2)$$

Kolz (1989) defined C_f as a measure of the behavioral response of a fish to an electrical stimulus, rather than as a purely physical measure linked solely to the resistive properties of the fish's tissues. The value of C_f was fixed at 115 as suggested by Miranda and Dolan (2003).

The D_m thresholds required to immobilize and injure fish were estimated in each of the 11 species–size treatments. The immobilization threshold for each treatment was selected as the lowest test D_m above which all individuals treated were immobilized within 3 s. Similarly, injury thresholds were selected as the lowest test D_m below which all individuals treated were not injured within a 15-s exposure period. The span between these two D_m boundary values was considered the margin for safe and effective electrofishing.

Application to boat electrofishing.—A major obstacle to standardized electrofishing is controlling the amount of power transferred into fish. The available technology for field electrofishing produces heterogeneous rather than homogeneous electrical fields, and therefore the actual field strength encountered by a fish depends on the location of the fish within the three-dimensional field. Fields vary widely in strength, the highest power densities being encountered near the electrodes (Kolz 1993). Homogeneous fields such as the one used in the laboratory portion of this study simulated one at a time the range of conditions encountered during field electrofishing and created controlled conditions that avoided many of the inconsistencies associated with data collected in a natural setting. Nevertheless, results must ultimately be applied to natural conditions. Thus, we undertook in-water measurements to describe the voltage gradient of heterogeneous fields and to link to thresholds identified by the tank study.

The boat electrofisher system used was similar to that described by Reynolds (1996). The 5.5-m-long boat had a flat-bottom aluminum hull and was equipped with two booms mounted at each corner of the bow on clutches. The clutches allowed vertical and horizontal adjustment of the booms. Each boom was 2.4 m long, and at the end supported an anode array 0.9 m in diameter. The array consisted of six droppers, each 1 cm in diameter, 1 m long, and spaced evenly around the perimeter of the array. The boat hull served as the cathode. When one dipper stood on the bow, the distance between the foremost waterline of the hull and the center of anode array was 2.8 m; the droppers penetrated 80 cm into water; and the distance between the centers of the anode arrays was 1.4 m. A Smith-Root GPP 7.5 system supplied electric power to the system.

Because of the impracticality of fully mapping voltage gradient in an entire three-dimensional electrofishing field, nine sample points were selected within the field, aided by a 2.0-m-wide × 1.5-m-long grid photographed by Henry et al. (2003). The grid was mounted on the electrode support booms, and the sample points were distributed 0.75 m apart from front to back, 1 m apart from left to right, for a total of nine points. These points were selected because they were considered to adequately represent the most central section of the field created by the test electrofishing boat, but depending on the equipment tested, other sampling points may be selected. These points did not include the zones immediately next to electrodes, which typically have high voltage gradients although they encompass only a minor fraction of the electrofishing field. At each of the nine points, peak voltage gradient was measured at depths of 0.1, 0.5, and 1.0 m, for a total of 27 measurements. The insulated rod used in the measurements contained two wires that extended 0.5 cm past the end of the rod and were set 1 cm apart, with insulation removed to expose about 2 mm of bare wire (described by Kolz 1993). The rod was connected to an oscilloscope to measure volts per centimeter at each of the sampling positions. For each measurement, the rod was rotated until the maximum voltage reading was identified. Power density applied (D_a, μW/cm^3) was computed as the product of water conductivity and voltage gradient squared (i.e., as per equation (1) with $d = 1$ cm). Rather than using a mean to describe the 27 D_a measurements in the field, D_a conditions were indexed with the 5th percentile (D_a^5) , so that 95% of the values measured in the electric field were larger than D_a^5 .

Concurrent with these voltage gradient measurements, the amount of peak power applied to the electrodes (P_a; W) was estimated as the product of peak current (I; amperes) and peak voltage. An oscilloscope was used to measure the peak voltage between the anode and cathodes and the peak current inline between the electrofisher and the electrodes. Although some electrofishers are equipped with meters to measure current and voltage, sometimes these meters provide relative readings (Van Zee et al. 1996) or just inaccurate readings (Pope et al. 2001), possibly because of aging of the internal system (Reynolds 2000).

Measures of D_a^5 were made at various levels of P_a to establish a relation that would allow predicting the P_a required to achieve a target D_a^5. Test levels were selected systematically so that P_a values would be roughly evenly distributed between a low P_a and the maximum P_a allowed by the limits imposed by the available equipment and water conductivities. All measurements were made at local lakes having water conductivities of 57–287 μS/cm and with the boat anchored over water at least 3 m deep. Regression analysis was used to derive parameters (b_0 and b_1) to quantify the relationship between P_a and D_a^5 for the test electrofishing boat as follows:

$$\sqrt{D_a^5} = b_1 \cdot P_a + b_0. \tag{3}$$

The resulting regression equation described the P_a required for achieving a specified D_a^5 in the test electrofishing boat. A square-root transformation of D_a^5 was necessary to linearize a curvilinear relation with P_a [the square-root transformation was chosen because derivation of D_a through equation (1) required squaring one of the terms]. The total power needed to immobilize fish and reduce risk of injury was estimated as follows:

$$P_a = \frac{-b_0 + \sqrt{D_m \cdot \frac{\left(1 + \frac{C_f}{C_w}\right)^2}{\left(4\frac{C_f}{C_w}\right)}}}{b_1}. \quad (4)$$

Equation (4) was derived by first rearranging equation (3) to solve for P_a; then rearranging equation (2) to solve for D_a; and lastly substituting D_a^5. in the rearranged equation (3) for the equality of D_a in the rearranged equation (2).

Validation of settings to avoid mortality.—The power targets identified in the laboratory as safe for electrofishing were tested by boat electrofishing at three medium-size impoundments (32–200 ha). Constant power transfer was maintained in waters with different conductivities by adjusting voltage and amperage in the GPP 7.5 electrofisher. Sampling within each lake was completed within three consecutive days, but sampling over all three lakes was completed within 5 weeks. At each site, electrofishing was conducted by maneuvering the boat at slow speed along the shoreline. Species belonging to the same genera as those tested in laboratory studies were held for 2–3 h in 150-L aerated plastic containers, filled with 140 L of local water. After the holding period, fish were identified according to species, measured for total length and for weight, and recorded as dead or alive; any live fish were released. Incidences of hemorrhages or spinal injuries were not assessed.

Results

Laboratory Assessments

In all, 314 fish were tested, including 29 controls. The mean total length of the study fish ranged from 44 to 343 mm and the weight from 1 to 385 g (Table 1). Water temperatures at which fish were held and tested ranged from 20°C to 28°C, and conductivity from 182 to 201 μS/cm. Although we strived to maintain ambient temperature conditions as constant as practicable, variability in water temperature had to be accepted, given the seasonal availability of test fish. If the range of experimental temperatures influenced reaction thresholds, it would have added random noise that reduced our ability to detect patterns of immobilization thresholds among species and size groups. Voltages applied in these water conditions ranged from 18 to 1,160 V, voltage gradients from 0.3 to 17.9 V/cm, D_a from 15 to 63,583 μW/cm^3, and D_m from 14 to 58,982 μW/cm^3. Estimates of D_m required to immobilize fish within 3 s ranged from 20 μW/cm^3 for large channel catfish to 330 μW/cm^3 for small largemouth bass (Figure 1).

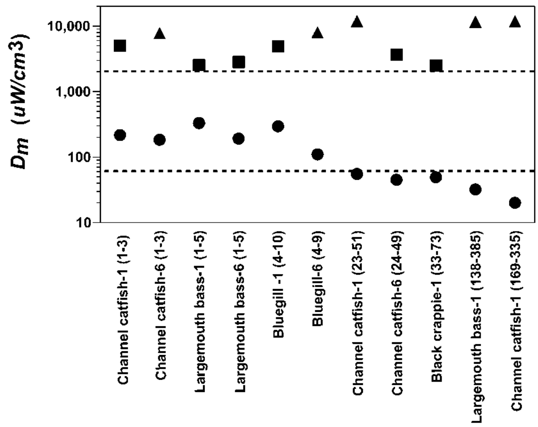

FIGURE 1.—Power density transfer (D_m, W/cm^3) levels required to immobilize (circles) and injure (squares) various species and size groups (gram weight ranges in parentheses). Triangles indicate no fish were injured and identify the highest power applied. The value of 1 or 6 trailing the species name indicates the fish were treated with 60-Hz pulsed DC with either 1 ms or 6 ms, respectively. The lower dashed lines identify the 60 μW/cm^3 level selected as the arbitrary target for electrofishing; the upper dashed line indicates the level below which no fish were injured.

Injuries to treatment fish ordinarily occurred mid-dorsally along the vertebral column. Spinal injury usually consisted of the compression of two to three vertebrae, without discernible fractures. Hemorrhages ranged from one to three vertebrae in diameter. Mortalities occurred over the first 2–3 h of the 18-h holding period, but most fish were probably killed during the 15-s exposure period because fish often appeared not to recover from tetanus. No hemorrhage, spinal injury, or mortality was observed in the control fish.

For treatment fish, whether exposed to enough power to immobilize or not, the incidence of hemorrhage averaged 4%, spinal injury was 1%, and mortality was 4%. When injuries were combined, 8% of the fish treated experienced at least one type of injury. Separated according to pulse width, the 1-ms treatment injured 9% of the fish treated, whereas the 6-ms treatment injured 7%; a chi-

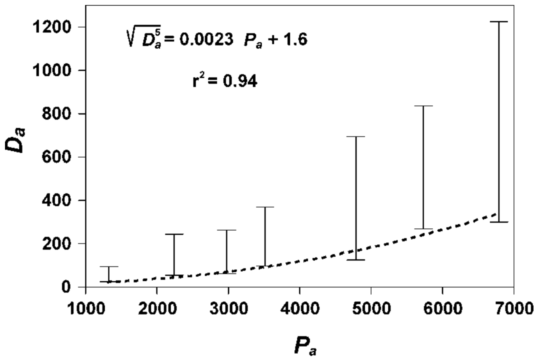

FIGURE 2.—Relationship between power applied to the electrodes (P_a, W) and the power density applied (D_a, μW/cm³) in the electric field. The vertical bars identify the range of D_a values over the 27 field measurements made at each level of P_a. The regression equation describes the average P_a required for achieving the 5th percentile of $D_a (D_a^5)$, and the dashed line identifies the predicted D_a^5.

square test of homogeneity indicated this difference was not statistically significant ($\chi^2 = 0.16$; df = 285; $P = 0.69$). Injury was observed on 6 of the 11 treatments, and mortality was more prevalent among small fish. The treatments injured 18% of the black crappie (0% died), 17% of the small largemouth bass (12% died), 4% of the small channel catfish (4% died), 2% of the medium-size channel catfish (0% died), 2% of the bluegills (2% died), and none of the large largemouth bass or large channel catfish. Nevertheless, no injury was observed in any of the treatments when D_m was held below 2,000 μW/cm³.

Application to Boat Electrofishing

Seven P_a levels were included ranging from 1,326 to 6,788 W (Figure 2). The 189 D_a values recorded (seven P_a levels by 27 measurements per level) ranged from 22 to 1,348 μW/cm³, and the D_a^5 values for the seven levels of P_a ranged from 25 to 300 μW/cm³. The curvilinear relation between P_a and D_a^5 was described with the model

$$\sqrt{D_a^5} = 0.0023 \cdot P_a + 1.6, \qquad (5)$$

where the slope parameter (0.0023) was significantly greater than zero ($P < 0.001$), but the intercept parameter (1.6) was not ($P = 0.14$). The r^2 for the model was 0.94, suggesting an adequate fit for predictive use.

A D_m of 60 μW/cm³ was arbitrarily selected as a target for electrofishing, based on the results from the laboratory tests. This level was expected to immobilize mostly fish larger than 20 g (Figure 1). Although the level selected would not entirely exclude fish smaller than 20 g, it would reduce the risk of exposure of small fish to potentially lethal power levels. Other target levels could have been selected, depending on the sampling objectives.

Adopting the 60 μW/cm³ level as the arbitrary target for electrofishing, the total power that must be output to transfer sufficient power to immobilize fish at a specific C_w within 95% of the electrofishing field considered was computed from equation (5) as follows:

$$P_a = \frac{-1.6 + \sqrt{60 \cdot \frac{\left(1 + \frac{115}{C_w}\right)^2}{\left(4\frac{115}{C_w}\right)}}}{0.0023}. \qquad (6)$$

Equation (6) was used to develop a schedule identifying the P_a required for immobilizing fish in various C_w conditions, given the arbitrary target D_m of 60 μW/cm³ (Table 2).

Validation of settings to avoid mortality.—Average water conductivity in the validation lakes ranged from 57 to 287 μS/cm, and average water temperature was 22–26°C. To achieve a constant average D_m of 60 μW/cm³, P_a targets ranging from 2,750 to 3,030 W were selected from Table 2. In all, 1,778 fish of 10 species were collected (Table 3). Of these, 11 (0.6%) died within the 2–3-h holding period. Five fish were unaccounted for and thus were excluded from mortality computations. All the fish killed were small, ranging in total length from 32 to 53 mm and in weight from 1 to 6 g.

Discussion

Standardization of electrofishing to improve consistency has many difficulties and uncertainties. Among the most notorious is the heterogeneous electric field created by the electrode array. With present technology, a heterogeneous field is unavoidable. However, management of power output and the electrode system to achieve reasonably steady fields can refine electrofishing. Another uncertainty is the estimate of fish conductivity needed to calculate power transfer. This value is likely to vary with species, life stage, nutritional status (e.g., condition), and perhaps other factors. Considering electrofishing targets multiple species and sizes and affects fish of diverse condition status, customizing fish conductivities is impractical. Nevertheless, relative to the high variability intro-

TABLE 2.—Target power outputs (P_a; W) for standardized eletrofishing at various ambient water conductivities (C_w; μS/cm). The target outputs are designed to transfer at least 60 μW/cm^3 into fish throughout most of the electrofishing field and can be achieved by manipulating amperage and voltage (W = A × V) with the electrofisher's controls. These target outputs are applicable only to the boat electrofisher system used in this study.

C_w	P_a	C_w	P_a	C_w	P_a	C_w	P_a
30	3,461	230	2,876	430	3,431	630	3,965
40	3,153	240	2,903	440	3,459	640	3,991
50	2,968	250	2,929	450	3,487	650	4,016
60	2,852	260	2,956	460	3,514	660	4,041
70	2,776	270	2,983	470	3,542	670	4,066
80	2,728	280	3,011	480	3,569	680	4,092
90	2,697	290	3,039	490	3,596	690	4,117
100	2,680	300	3,067	500	3,623	700	4,141
110	2,673	310	3,095	510	3,650	710	4,166
120	2,673	320	3,123	520	3,677	720	4,191
130	2,678	330	3,151	530	3,704	730	4,215
140	2,688	340	3,179	540	3,730	740	4,240
150	2,702	350	3,207	550	3,757	750	4,264
160	2,718	360	3,235	560	3,783	760	4,288
170	2,737	370	3,264	570	3,810	770	4,312
180	2,757	380	3,292	580	3,836	780	4,336
190	2,779	390	3,320	590	3,862	790	4,360
200	2,802	400	3,348	600	3,888	800	4,384
210	2,826	410	3,376	610	3,914	810	4,408
220	2,851	420	3,404	620	3,939	820	4,431

duced by the heterogeneous field, use of a fixed effective conductivity of 115 μS/cm was demonstrated to introduce little error into the estimation of standard power (Miranda and Dolan 2003).

Whereas the procedure described herein can promote consistency in electrofishing, it will not completely avoid harm to fish. Validation of the settings identified as harmless by the tank study produced less than 1% mortality in the field study. The target power transfer selected for electrofishing represented a value achieved in 95% of the points sampled. However, the anode probes and small parts of the field immediately next to the anode probes were likely to have high power. The laboratory tests indicated that no injuries occurred until D_m exceeded 2,000 μW/cm^3. Algebraic manipulation of equation (2) to solve for voltage gradient would suggest that, at the 57 μS/cm water conductivity encountered in one of the lakes included in the validation study, voltage gradients higher than 6.3 V/cm would produce D_m levels that exceeded 2,000 μW/cm^3. Henry et al. (2003) reported voltage gradient vectors within 5 cm of the anode for five electrofishing boats that ranged from 16 to 20 V/cm in all cases (at 45 μS/cm and 15–17°C, this translates to D_m levels of 14,000–22,000 μW/cm^3). Conceivably, the specimens harmed by the sampling came in direct contact with the anode

TABLE 3.—Counts of fish collected in three lakes to validate settings thought to avoid mortality from eletrofishing. The values in parentheses under each lake heading represent the water conductivity (μS/cm) and total power applied (W), repectively. The values in parentheses next to each count represent the number of fish killed by the sampling process.

Species	Lake 1 (57; 2,880)	Lake 2 (178; 2,750)	Lake 3 (287; 3,030)	Weight range (g)
Blue catfish *Ictalurus furcatus*	4	0	0	358–1,137
Channel catfish	25	6	4	9–2,994
Green sunfish *Lepomis cyanellus*	17	2	2	4–96
Warmouth *L. gulosus*	48	20	50	3–131
Bluegill	255 (4)	307	314 (3)	1–295
Longear sunfish *L. megalotis*	44	137 (1)	64 (1)	1–244
Redear sunfish *L. microlophus*	0	64	20	4–268
Largemouth bass	68	80	41	10–2,726
White crappie *Pomoxis annularis*	23 (1)	46	55 (2)	5–1,007
Black crappie	45	27	10	11–592
All species	529 (5)	689 (1)	560 (5)	1–2,994

droppers or with high voltage gradients near the vicinity of the droppers. Intense voltage gradients may be dissipated by increasing the surface area of the electrodes, as suggested by Novotny (1990), or possibly by surrounding the droppers with a protective plastic netting tubular system that would prevent direct contact with fish and keep fish at safe distance. However, such modifications may have disadvantages associated with providing the desirable mechanical features that allow the droppers to negotiate submerged and emerged obstacles.

Because electrode arrays are often not standard among boats, the observed relationship between P_a and D_a^5 (Figure 2; Table 2) is pertinent only to the boat electrofisher used in this study. Indeed, the relationship is likely to change not only in relation to electrode system array but also in relation to the fish species and size, as well as for the waveform and duty cycle for which it was developed. Immobilization thresholds of electrofishing have been linked primarily to fish size, with large fish requiring less power to immobilize (Dolan and Miranda 2003). Nevertheless, morphological and neurological adaptations of various species also have been reported to affect fish response to electric fields (Halsband 1967; Peters and Bretschneider 1972; Lamarque 1990). The target values derived in the present study were similar to the 3,000-W target developed by Burkhardt and Gutreuter (1995) for 60-Hz pulsed DC electrofishing, but they were developed with a different approach and for different electrode arrays. The similarities probably were promoted by the wide-ranging similarities among boat electrofishers. An incomplete review of methods described in gray literature produced after Burkhardt and Gutreuter (1995) identified 3,000 W as their target power revealed that this target has sometimes been adopted not only in boats with different electrode arrays but also with applied pulse frequencies different from those reported by Burkhardt and Gutreuter (1995). This latter change is not recommended because power requirements vary greatly with pulse frequency (Miranda and Dolan 2004).

Although the procedure used here targeted standardization of a single boat so that electrofishing power could be held constant over time and space, expansion to standardizing a fleet of electrofishing boats might be the next desired step. Identical electrofishers connected to dissimilar electrode arrays cannot produce identical fields, even if waveform, voltage, and amperage are held constant. Use of boats rigged with identical equipment and electrode arrays is the simplest way to produce identical fields and is recommended. Nevertheless, identical equipment is not always practicable because of the need to adapt selected components of an electrofishing system to meet local demands. However, equipment may be calibrated across boats through adjustments of individual components, so that each boat can generate electrical fields that are similar in dimensions and power distributions. Such calibration entails in-water measurement to quantify the voltage gradients of individual fields, to allow their comparison across electrofishing systems as described by Henry et al. (2003). Calibration is recommended even when boats rigged with identical equipment are used.

Approaches other than the one applied in this study may be suitable for achieving a chosen level of standardization. If the goal is solely to improve consistency, then simply establishing a permanent waveform, an electrode design and array, and a power target will suffice. The target may be derived from knowledge of proven power levels accumulated from past surveys, as done by Burkhardt and Gutreuter (1995); from field trials designed to identify optimum power levels, as done by Bonar et al. (2000); or from controlled trials, as done in this study. If the goal of standardization also includes reducing or eliminating injury to fish, then thresholds for immobilization must be considered in relation to thresholds for injury. Bonar et al. (2000) established these thresholds in field trials over a range of power settings and then selected the lowest power that immobilized fish but did not injure them. Tank studies such as the ones in the present study can provide more control and thus more consistent estimates of injury thresholds. Alternatively, a literature review may yield the necessary estimates, given that data relating injury to electric fields is accumulating rapidly (Appendix B in Snyder 2003 provides a compendium of references according to fish species and waveforms). Once targets have been identified, a schedule such as that shown in Table 2 may be constructed to facilitate matching water conductivity with the power output and thus achieve a standard power transfer.

Refining electrofishing to improve consistency and reduce injury is critical when this gear is used to monitor temporal and spatial changes in fish assemblages. Standardization of the power transferred to fish can reduce variability of survey data and potentially reduce injury to fish. In one study, standardization of power improved predictability of electrofishing catch rates by about 15% (Burkhardt and Gutreuter 1995). Electrofishing-induced injury and mortality can often be linked to exposure to excessive power levels (Snyder 1995), and thus standardization of power to avoid risky levels can minimize injury. Nevertheless, because electrofishing is an active capture method applied to changing microenvironments, the combination of complete standardization and total avoidance of harm to individual fish is not feasible with present technology, but standardization of controllable variables is advisable.

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